SINGLE CRYSTAL FIBER AMPLIFIERS FOR ULTRASHORT PULSES LASERS

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In laser micro-processing, short pulses translate to precision and accuracy while high average power leads to higher processing speed with high energy providing processing capability. Short pulses can be readily achieved, but in such regime scalability in terms of energy or average power is more challenging. For instance, amplification in fibers is limited in peak power by non-linear effects. A well-accepted solution to achieve high power in a short pulse width laser is a MOPA (Master Oscillator Power Amplifier) architecture using various techniques and materials for the amplification.

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BULK CRYSTAL AMPLIFIERS

Bulk crystals amplifiers suffer from beam degradation due to the strongly aberrant thermal lensing effect created inside the material. Because of this fundamental limitation, high power amplifiers evolved in several directions to better manage the heat inside the gain medium: thin disks, slabs and special fibers.

Thin disks present a limited gain per pass, due to the small thickness (typ. 100 µm) of the gain medium. As a consequence, amplification with thin disks can be achieved either by multipass amplifiers or regenerative amplifiers. Multipass amplifiers requires a complex optical setup, with typically more than 10 bounces on the crystal. Regenerative amplifiers require the use of electro-optics modulators, increasing cost and once again complexity.

Despite those drawbacks, thin disk amplifiers can generate very high output power (above the kW level) and are very well suited as high power final amplification stage.

High gain are achieved in slab amplifiers leading to very high average power, up to the kW level, but the complex path of the amplified laser can introduce beam ellipticity and degraded beam quality.

FIBER AMPLIFIERS

To circumvent peak power limitation of single mode fibers, Fiber laser amplifiers for short pulses use either LMA (Large Mode Area), or PCF LMA (Photonics Crystal Fibers with Large Mode Area) fibers. The highest peak powers are achieved with PCF rod-type fibers. The maximum core diameter of the commercially available fiber is 85 µm with a propagating mode of 65 µm and, even though doping level can be quite high, typical length is around 1 m. To provide diffraction limited beam, the fiber design is no longer flexible due to the very large core and extremely low numerical aperture, leading to voluminous systems. The overlap between the guided pump and the guided laser mode leads to a good optical efficiency; average power up to 200W with a good beam quality can be achieved although, at high average power, thermo-optical effects significantly influence the waveguiding mechanism. These perturbations causes LMA fibers to also support higher order modes at high power, which leads to beam quality degradation and eventually to output beam fluctuations on the millisecond time scale (transverse mode instability). In industrial laser systems, the peak power in rod-type fibers is generally limited around 1 MW to avoid non-linear effects.

Chirped pulse amplification alleviates this limitation for femtosecond fiber lasers, and high power systems based on 40 µm core flexible PCF fibers are released on the market. However, the peak power limit forces to use large stretching ratio and large compressors, increasing the cost and system size.

SINGLE CRYSTAL FIBERS

A single-crystal fiber (SCF) is a single-crystal, usually YAG, with a long length, a small diameter and attractive light guiding properties.

Laser Heated Pedestal Growth (LHPG) produces small diameter fibers (around 100 µm diameter). Great improvement were made recently in the crystal quality, and the final goal of those developments is to achieve a core/clad structure similar to classical fibers for high average power laser systems.

However, the production of the core/clad structure is a very difficult challenge far from being solved, particularly when polarization maintaining is needed, and the resulting architecture would suffer from the same limitation than silica fibers for high peak power pulses. This would be even aggravated by the higher non-linear properties of YAG compared to glass, so this solution is clearly not fitted for ultrafast high power amplifiers.

Larger diameter, 1mm to 2mm, SCF are produced using micro pulling down technique and have demonstrated the ability to sustain MWatts of peak power. They are ideal candidate for high-energy short pulse amplification.

SINGLE CRYSTAL FIBER PUMPING

The preferred configuration for amplification uses SCF 1 mm in diameter and 30 to 50 mm long, generally produced in Nd:YAG or Yb:YAG and for ultra short laser systems, Yb:YAG is preferred because of its advantageous spectroscopic properties such as larger absorption and emission bandwidth, longer upper-laser level lifetime, lower thermal loading per unit pump power. Commercial SCF amplifiers, such as the Taranis laser gain modules, uses a specific pumping scheme: the pump beam is focused in a 400 µm diameter spot inside the crystal, not on the crystal surface but deep enough to maximize the amplifier output. The highly divergent beam is then guided by total internal reflection and refocused again in the gain medium.

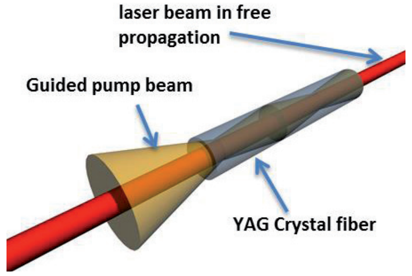

Figure 1: *Principle of SCF amplifier*

Fibercryst Technical Bulletin // **Single Crystal Fiber amplifiers for Ultrashort Pulses Lasers** // December 2016

The initial focusing point of the pump is imaged several times along the fiber length, depending on the pump brightness.

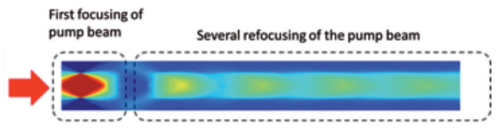

Figure 2: *Example of pump propagation*

The pump beam is kept collinear to the laser beam during the propagation in the gain medium, avoiding off-axis aberrations that can appear in slabs or thin disks such as astigmatism, therefore leading to superior beam quality. The doping is typically one order of magnitude lower than in usual bulk crystals, and the length typically one order of magnitude higher. Without pump guiding, this would be useless because of the high divergence of the pump. But combined with pump guiding, this long length/low doping rate ratio enables to dispatch the pump absorption along the entire crystal fiber length and therefore to lower thermal stress in the gain medium.

SINGLE CRYSTAL FIBER AMPLIFIERS

Single Crystal Fibers in a MOPA configuration have already proven its efficiency and flexibility in the field. In practical term, Yb:YAG SCF gain modules produced by Fibercryst were pumped up to 600 W at 940 nm without damage [1], far above the typical pumping level of usual bulk crystals.

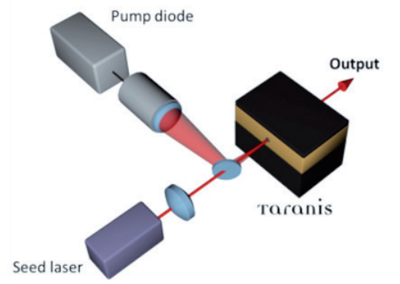

Figure 3: *Amplifier setup with SCF integrated into a Taranis Module supplied by Fibercryst*

Cooling a 1 mm diameter YAG rod submitted to hundreds Watts of pump is not an easy challenge, but this issue was solved by the development of the Taranis module, a technology patented by Fibercryst and the CNRS-LCF laboratory to integrate the crystal fiber directly into a metallic mount. The achieved cooling is very efficient, with a thermal exchange coefficient up to 5 W/cm /K, 5 times better than classical indium pressed solutions.

Figure 4: *Water cooled Taranis Module*

The thermal gradient in the pumped crystal fiber is also radially symmetrical, to guarantee once again an excellent beam quality even at high power. High average power of 140 Watt has been achieved without reaching the limit of the SCF technology [2].

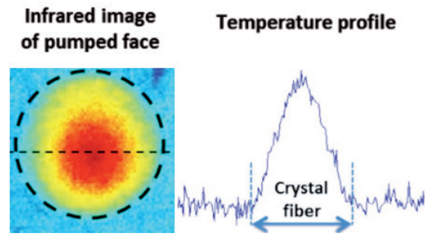

Figure 4: *Thermography image of a pumped SCF module*

HIGH AVERAGE POWER AND HIGH ENERGY

In a rod-type amplifier, the typical surface of the laser mode is 3000 µm². Non-linear effects like SPM (Self Phase Modulation) or Raman quickly appear when high peak intensities are propagated in such small surfaces and long length of interaction. In a typical SCF amplifier, the surface covered by the laser mode is 50 times higher, and as a consequence substantially higher peak powers can be achieved.

With SCF technology, the combination of high gain, small length, and large beam diameters already demonstrated small signal gain around 30 dB, and peak powers up to 50 MW [3].

As an improved "bulk crystal" amplifier, the SCF technology keeps all the considerable advantages of usual bulk amplifiers, especially their ability to operate independently over a large range of repetition rate, pulse duration and seed power. The same SCF amplifier can be used, with no adjustment, to amplify a pulsed seed laser from a few kHz to several tens of MHz, or a seed laser from 10's of ns down to a few hundred of femtoseconds. Seed powers from a few hundred of mW up to tens of Watts were already successfully amplified [4][5].

SIMPLICITY AND PERFORMANCE

A typical single pass Yb:YAG SCF amplifier stage, in an industrial product, is composed of six optics, with only standard optical components and pump optics included. This compares very well with disk or slab technologies.

The SCF amplifiers are used with a variety of seeder lasers demonstrating the flexibility and the simplicity of the amplifier setup.

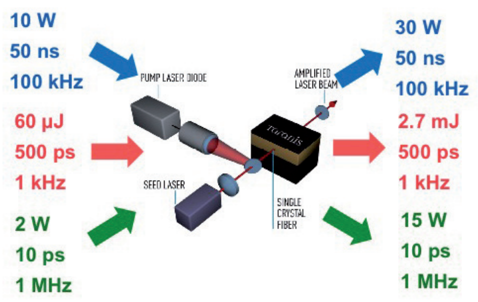

Figure 6: *Examples of Nd:YAG SCF operation*

For example, we report an architecture based on SCF associated with a DPA (Divided Pulse Amplification) setup and dedicated to high energy, providing 6 ps pulses with an energy of 2 mJ at the repetition rate of 12,5kHz [3]. Regarding average power oriented amplifiers. A system delivering 100 W without CPA has been obtained. The repetition rate is 20 MHz and the pulse width is 750 fs [6]. In both configurations, output beam quality was excellent, with M below 1.2.

FROM AMPLIFIERS TO LASERS

The technical benefits of the Single Fiber Crystal technology have enabled Fibercryst to develop a line of high power short pulse lasers for industrial applications. With a novel architecture using SCF amplifiers in cascade, associated to a femtosecond seeder, the FEMTO25 industrial laser covers a very large set of performance. The simplicity of the Taranis modules and their proven stability in the field results in a rugged, stable laser that requires no tweaking. Since the SCF amplifier technology preserves the beam quality, the FEMTO25 presents excellent M^2 and ellipticity. The energy per pulse of this laser can be changed at a flick of a button for process development. Moreover, the overall modularity of the laser enables a great flexibility of performance to adapt to any kind of applications.

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